Appendix D: Mechanical Equipment Example

D-1. Description

For this analysis, the individual mechanical gate systems are considered subsystems to the overall lock and dam system. The example lock miter gate and valve machinery subsystems are laid out as shown in Figures D-1 and D-2. The dam gate machinery is laid out as shown in Figure D-3.

D-2. Reliability Block Diagram Formulation

Formulation of the system reliability block diagram (RBD) is in accordance with MIL-STD-756B. The initial step in determining the reliability of the mechanical systems of the lock and dam is to identify the function or mission of the machinery. The machinery function is to operate the gates. The major components required for mission success are defined and organized into an RBD. The block diagrams for the miter gate and tainter valve and dam gate components included in this evaluation are shown in Figures D-4, D-5, and D-6. The RBD is simplified or expanded, if necessary, to sufficient detail to allow determination of component failure rate from published data. The process continues until only blocks with published component failure rate data remain in the block reliability model. In this example, the structural supports are not included in the model. They are unique to each system, and no published data are available. For the lock and dam gate and valve machinery shown in the figures, the failure of any one component constitutes nonperformance of the mission. There are no parallel or redundant items. The mission and basic block diagrams will be series models.

D-3. Reliability Calculation

The basic and mission reliability model blocks should be keyed with consistent nomenclature of elements. Each model should be capable of being readily updated with new information resulting from relevant tests, as well as any changes in item configuration or operational constraints. Hardware or functional elements of the system not included in the model shall be identified. Rationale for the exclusion of each element from the model shall be provided.

a. Duty cycle. The mission or function of the system should address the duty cycle or period of operation. The miter gate equipment is considered to have a negligible failure rate during periods of non-operation (ignoring barge impact). The failure rate can be modified by a duty cycle factor. The duty cycle factor is the ratio of actual operating time to total mission time t. For example, the equation $R(t) = e^{-\lambda td}$ is the exponential failure rate distribution with a duty factor d. The duty factor for lock mechanical equipment is directly related to the number of lockages or hard operations that occur at a facility. The number of lockages may vary over time, and hence the duty factor may vary. In this example, the lockages or cycles increase with time. The duty factor is calculated for each year as follows: For year 5, the lock performs 11,799 open/close cycles. Assuming the operating time of an open or close operation is 120 seconds (or 240 seconds per open/close cycle) and using a total mission time of 8760 hours per year then,

$$
\begin{aligned}
\text{Operating time} &= (240*11{,}799)/3600 \\
&= 786.6 \text{ operational hours/year} \\
&= 786.6/8760 \text{ hours/year} \\
d &= 0.0898
\end{aligned}
$$

b. Environmental conditions. Environmental conditions shall be defined for the ambient service of the equipment. An approximate approach (Green and Bourne 1972) multiplies failure data by various K

factors to relate the data to other conditions of environment and stress where K is the environmental factor adjustment coefficient used to represent component stress levels altered by environmental conditions. Typical K factors are given in Table D-1 where K_1 relates to the general environment of operation, K_2 to the specific rating or stress of the component, and K_3 to the general effect of temperature. The equipment on the lock is considered to be exposed to an outdoor marine environment. For this example, a K_1 factor of 2 is used and K_2 and K_3 are 1.0.

c. Lock equipment reliability. The Weibull distribution was used to perform the reliability analysis for each component in the block diagram. The values for β were selected from the values given in Table 7-2 of Bloch and Geitner (1994), and reproduced as Table D-2, by choosing a dominant failure mode for each component. If β cannot be determined, a value of 1.0 should be used. It should be noted that most of the β values in Table D-2 are greater than or equal to 1.0, but not greater than 3.0. These values represent random and wear-out failures as indicated by Regions B and C of the bathtub curve. The characteristic life parameter α is determined from the failure rate data. Table D-3 contains failure rates for several common mechanical components found on locks and dams. Appendix C contains a table of failure rate data for lock and dam equipment. This table was generated from data entered in the Web site database for Corps equipment. While α is normally determined through experimental methods, it can be approximated from the ratio of α to Mean Time to Failure (MTTF) as a function of β by using Table D-4. For example, the dominant failure mechanism for the spur gears is considered to be wear such as fretting, scoring, or pitting. From Table D-2, the shape parameter β (Weibull Index) is 3.0, and from Table D-4 α/MTTF = 1.10. The life parameter α is calculated as follows:

(1) Table D-3 was used as the source for the failure rate data. These values are taken from a higher number of sources and have less variability. From the published data of Table D-3, the summary or combined failure rate λ computed from all individual data sources for spur gears is given as 3.2232 failures per million operating hours. The environmental factors are $K_1=2$, $K_2=K_3=1$.

(2) The adjusted failure rate λ′ is

$$\lambda' = \lambda K_n \tag{D-1}$$

$$\lambda' = 3.2232 * K_1 * K_2 * K_3 = 6.446 \text{ failures per million operating hours}$$

and

$$\begin{aligned} \text{MTTF} &= 1/\lambda' \\ &= 1/6.446 = 0.155 \times 10^6 \text{ hr} \end{aligned} \tag{D-2}$$

therefore

$$\begin{aligned} \alpha &= \text{MTTF} * 1.1 \\ &= 0.155 \times 10^6 * 1.1 = 0.17 \times 10^6 \text{ hr} \end{aligned} \tag{D-3}$$

$$\alpha = 0.17 \times 10^6/8760 = 19.4 \text{ years}$$

(3) The Weibull reliability function from the main text for the components becomes

$$R(t) = \exp\left[-\left(\frac{td}{\alpha}\right)^{\beta}\right] \tag{D-4}$$

where time t is in years. The Weibull hazard function becomes

$$h(t) = \frac{\beta}{\alpha}\left(\frac{td}{\alpha}\right)^{\beta-1} \tag{D-5}$$

(4) For this example, the electric motors were considered electrical devices and are not included in this reliability analysis. They are evaluated in the electrical analysis. The mechanical system was considered to begin at the first coupling. The reliability for the miter gate machinery model of Figure D-4 at time *t* is calculated as

$$R_{SYS}(t) = R_A(t)^3 * R_B(t)^2 * R_C(t) * R_D(t) * R_E(t)^2 * R_F(t)^2 * R_G(t)^2 \tag{D-6}$$

(5) The reliability for the tainter valve machinery model of Figure D-5 is calculated as

$$R_{SYS}(t) = R_A(t)^4 * R_B(t)^2 * R_C(t) * R_D(t) * R_E(t)^4 * R_F(t)^3 \tag{D-7}$$

The tainter valve hoist drums and wire rope were not modeled because no failure data were available. Also, these items are organized in parallel so their combined reliability value is much higher than the other components.

d. Dam equipment reliability. The dam machinery block diagram is shown in Figure D-6. The system was considered a series model since the unreliability of one component will cause the entire system to be inoperable. The duty factor for dam equipment is not directly related to the number of lockages. The duty factor was determined as follows:

Assume 2 gate changes per day at 5 min each.

d = (2*5)min/day*365 days/year/60/8760 hrs/year = 0.007

The dam gate system reliability calculation is similar to that for the lock machinery:

$$R_{SYS}(t) = R_A(t) * R_B(t)^{10} * R_C(t) * R_D(t)^4 * R_E(t)^{16} * R_F(t)^6 * R_G(t)^4 \tag{D-8}$$

D-4. Results

a. Lock equipment. The analyses for each major component of the miter gate and tainter valve systems for 50 years of service are contained in spreadsheet format in Tables D-5 and D-6, respectively. The values in the tables are shown rounded to the nearest four decimal places; however, they are not rounded for the mathematical analysis. As a result, some components show a reliability value of 1.0 in future years when their hazard rates are nonzero. The system reliability for the miter gate and valve machinery drops to 41 and 33 percent, respectively, after 50 years. It should be noted that the brakes and the gear reducers have the highest hazard rates, which indicates a higher susceptibility to failure. The electric motors for this analysis were considered electrical equipment and are not included in the mechanical analyses.

b. Dam equipment. The results are tabulated in Table D-7. The dam machinery is 82 percent after 50 years. Because failure data on the sprocket were not available, it was not included in the analysis.

Table D-1
Overall Environment Component Stress Levels (data from Greene and Bourne 1972)

General Environmental Condition	K_1
Ideal, static conditions	0.1
Vibration-free, controlled environment	0.5
General purpose ground based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0
Stress Rating	
Percentage of component nominal rating	K_2
140	4.0
120	2.0
100	1.0
80	0.6
60	0.3
40	0.2
20	0.1
Temperature	
Component temperature (degrees C)	K_3
0	1.0
20	1.0
40	1.3
60	2.0
80	4.0
100	10.0
120	30.0

Note: Other data sources such as Reliability Analysis Center (1995) also contain environmental information.

Table D-2. Primary Machinery Component Failure Modes (Bloch and Geitner 1994)

Failure Mode	Weibull Index β	Standard Life
Deformation		
Brinelling	1.0	Inf
Cold flow	1.0	Inf
Contracting	2.0	Inf
Creeping	2.0	Inf
Bending	1.0	Inf
Bowing	1.0	Inf
Buckling	1.0	Inf
Bulging	1.0	Inf
Deformation	1.0	Inf
Expanding	1.0	Inf
Extruding	1.0	Inf
Growth	1.0	Inf
Necking	1.0	Inf
Setting	2.0	Inf
Shrinking	2.0	Inf
Swelling	3.0	Inf
Warping	1.0	Inf
Yielding	1.0	Inf
Examples:		
Deformation of springs	1.0	Inf
Extruding of elastomeric seals	1.0	4.0Y
Force-induced deformation	1.0	Inf
Temperature-induced deformation	2.0	Inf
Yielding	1.0	Inf
Fracture/Separation		
Blistering	1.0	Inf
Brittle fracture	1.0	Inf
Checking	1.0	Inf
Chipping	1.0	Inf
Cracking	1.0	Inf
Caustic cracking	1.0	Inf
Ductile rupture	1.0	Inf
Fatigue fracture	1.0	Inf
Flaking	1.0	Inf
Fretting fatigue cracking	1.0	Inf
Heat checking	1.0	Inf
Pitting	1.0	Inf
Spalling	1.0	Inf
Splitting	1.0	Inf
Examples:		
Overload fracture	1.0	Inf
Impact fracture	1.0	Inf
Fatigue fracture	1.1	Inf
Most fractures	1.0	Inf
Change of Material Quality		
Aging	3.0	5.0Y
Burning	1.0	Inf
Degradation	2.0	3.0Y
Deterioration	1.0	Inf
Discoloration	1.0	Inf
Disintegration	1.0	Inf
Embrittlement	1.0	Inf
Hardening	1.0	Inf
Odor	1.0	Inf
Overheating	1.0	Inf
Softening	1.0	Inf

Note: Inf = Infinite
M = Month(s)
Y = Year(s)

(Sheet 1 of 3)

Table D-2 (Continued)

Failure Mode	Weibull Index β	Standard Life
Examples:		
Degradation of mineral oil-based lubricant	3.0	1.5Y
Degradation of coolants	3.0	1.0Y
Elastomer aging	1.0	4.0-16Y
O-Ring deterioration	1.0	2.0-5Y
Aging of metals under thermal stress	3.0	4.0Y
Corrosion		
Exfoliation	3.0	2.0-4.0Y
Fretting corrosion	2.0	3.0Y
General corrosion	2.0	1.0-3.0Y
Intergranular corrosion	2.0	1.0-3.0Y
Pitting corrosion	2.0	1.0-3.0Y
Rusting	2.0	0.5-3.0Y
Staining	2.0	0.5-3.0Y
Examples:		
Accessible Components	2.0	2.0-4.0Y
Inaccessible Components	2.0	2.0-4.0Y
Wear		
Abrasion	3.0	0.5-3.0Y
Cavitation	3.0	0.5-3.0Y
Corrosive wear	3.0	0.5-3.0Y
Cutting	3.0	0.5-3.0Y
Embedding	3.0	0.5-3.0Y
Erosion	3.0	3.0Y
Fretting	3.0	2.0Y
Galling	3.0	2.0Y
Grooving	3.0	2.0Y
Gouging	3.0	2.0Y
Pitting	3.0	1.0Y
Ploughing	3.0	1.0Y
Rubbing	3.0	3.0Y
Scoring	3.0	3.0Y
Scraping	3.0	0.5-3.0Y
Scratching	3.0	3.0Y
Scuffing	3.0	1.0Y
Smearing	3.0	1.0Y
Spalling	3.0	0.5-16Y
Welding	3.0	0.5-3.0Y
Examples:		
Non-lubed relative movement	3.0	1.0Y
Contaminated by lubed sleeve bearings	3.0	3.0M
Spalling of antifriction	3.0	4.0-16Y
Bearings	1.1	16.0Y
Displacement/seizing/adhesion:		
Adhesion	1.0	Inf
Clinging	1.0	Inf
Binding	1.0	Inf
Blocking	1.0	Inf
Cocking	1.0	Inf
Displacement	1.0	Inf
Freezing	1.0	Inf
Jamming	1.0	Inf
Locking	1.0	Inf

(Sheet 2 of 3)

Table D-2 (Concluded)

Failure Mode	**Weibull Index β**	**Standard Life**
Displacement/seizing/adhesion:		
Loosening	1.0	Inf
Misalignment	1.0	Inf
Seizing	1.0	Inf
Setting	1.0	Inf
Sticking	1.0	Inf
Shifting	1.0	Inf
Turning	1.0	Inf
Examples:		
Loosening (locking fasteners)	1.0	Inf
Loosening (bolts)	1.0	Inf
Loosening	1.0	Inf
Misalignment (process pump set)	2.0	1.5-3.0Y
Seizing (linkages)	1.0	Inf
Seizing (components subject to contamination or corrosion)	1.0	Inf
Shifting (unstable design)	1.0	Inf
Leakage:		
Joints with relative movement	1.5	3.0M-4.0Y
Joints without relative movement	1.0	16.0Y
Mechanical seal faces	0.7-1.1	0.5-1.5Y
Contamination		
Clogging	1.0	Inf
Coking	2.0	0.5-3.0Y
Dirt accumulation	2.0	0.5M-3.0Y
Fouling	1.0	Inf
Plugging	1.0	Inf
Examples:		
Fouling gas compressor	3.0	1.5-5.0Y
Plugging of passages with moving medium	1.0	Inf
Plugging of passages with nonmoving medium	1.0	Inf
Conductor Interruption		
Flexible cable	1.0	Inf
Solid cable	1.0	Inf
Burning through Insulation		
Motor windings	1.0	16Y
Transformer windings	1.0	16Y

(Sheet 3 of 3)

Table D-3
Failure Rate Data of Mechanical Components

Component[1]	Failure Rate per 10^6 Operating Hours
Bearings (Summary)	2.9151
Ball (Summary)	1.6445
Roller (Summary)	2.8201
Sleeve (Summary)	2.3811
Couplings, Shaft (Summary)	1.0038
Flexible	1.4054
Rigid	2.6347
Shafts (Summary)	0.9298
Gear Box (Summary)	8.7082
Reducer, Worm	5.0000
Reducer, Spiral Bevel	5.0000
Gear Train (Summary)	3.4382
Gear, Spur	3.2232
Gear, Helical	2.6008
Gear, Worm	3.8258
Gear, Bevel	1.4722
Gear, Rack	1.7562
Brake, Assembly	2.1000
Brake, Electromechanical	10.6383
Hydraulic Cylinder	0.0080
Valves	
Ball (Summary)	0.2286
Butterfly (Summary)	0.2900
Check (Summary)	0.0773
Gate (Summary)	0.0478
Globe (Summary)	0.1439
Hydraulic (Summary)	8.8292
Ball	2.3841
Bellows Diaphragm	14.8953
Check	5.3725
Control	57.7196
Relief	0.9201
Solenoid	25.0590
Seal (Summary)	5.4715
Packing	3.5308
O-ring	4.6511
Gaskets (Summary)	0.0195
Springs (Summary)	0.6134
Pump	
Hydraulic (Summary)	46.9604
Centrifugal	10.4022
Fixed Displacement	1.4641
Positive Displacement	9.5620
Motor Driven	12.9870
Variable Delivery	54.0498
Centrifugal	51.1732
Piping (Summary)	0.4734

[1] Failure rates are from Reliability Analysis Center (1995). The data including the summary data represent combined failure rate data, which is a weighted merger of several failure rates.

Table D-4
α/MTTF Ratio as a function of β (Reliability Analysis Center 1995)

β	α/MTTF
1	1.00
2	1.15
2.5	1.12
3.0	1.10
4.0	1.06

Table D-5
Reliability Analysis, Lock Miter Gate Machinery

Component/Block	Quan.	Failure Rate*	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α, Yrs
Couplings	3	1.4054	misalignment	1.0	1.00	2	40.6131
Antifriction Bearing	2	1.6445	wear	3.0	1.10	2	38.1790
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798
Gear Reducer	1	5.0000	wear	3.0	1.10	2	12.5571
Plain Bronze Bearings	2	2.3811	wear	3.0	1.10	2	26.3682
Spur Gears	2	3.2232	wear	3.0	1.10	2	19.4792
Shafts	2	0.9298	fracture	1.0	1.00	2	61.3870

DUTY FACTOR, d

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Number of Cycles	12758	11799	12336	12514	12692	12841	12991	13249	13508	13754	14000
	0.0971	0.0898	0.0939	0.0953	0.0966	0.0978	0.0989	0.1009	0.1029	0.1047	0.1066

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	1.0000	0.9890	0.9771	0.9654	0.9535	0.9416	0.9295	0.9167	0.9037	0.8904	0.8770
Antifriction Bearings	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9995	0.9992	0.9987	0.9981	0.9973
Brake	1.0000	0.9836	0.9660	0.9488	0.9314	0.9140	0.8966	0.8782	0.8595	0.8408	0.8219
Gear Reducer	1.0000	1.0000	0.9996	0.9985	0.9964	0.9927	0.9869	0.9780	0.9654	0.9485	0.9264
Plain Bronze Bearings	1.0000	1.0000	1.0000	0.9998	0.9996	0.9992	0.9986	0.9976	0.9962	0.9943	0.9918
Spur Gears	1.0000	1.0000	0.9999	0.9996	0.9990	0.9980	0.9965	0.9941	0.9906	0.9859	0.9797
Shafts	1.0000	0.9927	0.9848	0.9770	0.9690	0.9610	0.9528	0.9441	0.9352	0.9261	0.9168

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Antifriction Bearings	0.0000	0.0000	0.0000	0.0001	0.0002	0.0003	0.0005	0.0007	0.0009	0.0012	0.0015
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Gear Reducer	0.0000	0.0003	0.0013	0.0031	0.0057	0.0091	0.0133	0.0189	0.0256	0.0336	0.0430
Plain Bronze Bearings	0.0000	0.0000	0.0001	0.0003	0.0006	0.0010	0.0014	0.0020	0.0028	0.0036	0.0046
Spur Gears	0.0000	0.0001	0.0004	0.0008	0.0015	0.0024	0.0036	0.0051	0.0069	0.0090	0.0115
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [R_{sys}(t)]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9376	0.8734	0.8127	0.7531	0.6952	0.6382	0.5791	0.5203	0.4624	0.4054

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995)

Table D-6
Reliability Analysis, Lock Tainter Valve Machinery

Component/Block	Quan.	Failure Rate*	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α, Yrs
Couplings	4	1.4054	misalignment	1.0	1.00	2	40.6131
Ball Bearing	2	1.6445	wear	3.0	1.10	2	38.1790
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798
Gear Reducer	1	5.0000	wear	3.0	1.10	2	12.5571
Roller Bearings	4	2.8201	wear	3.0	1.10	2	22.2635
Shafts	3	0.9298	fracture	1.0	1.00	2	61.3870
Wire Rope Drums	2	Information not Available					

DUTY FACTOR, d

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Number of Cycles	12758	11799	12336	12514	12692	12841	12991	13249	13508	13754	14000
	0.0971	0.0898	0.0939	0.0953	0.0966	0.0978	0.0989	0.1009	0.1029	0.1047	0.1066

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	1.0000	0.9890	0.9771	0.9654	0.9535	0.9416	0.9295	0.9167	0.9037	0.8904	0.8770
Ball Bearing	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9995	0.9992	0.9987	0.9981	0.9973
Brake	1.0000	0.9836	0.9660	0.9488	0.9314	0.9140	0.8966	0.8782	0.8595	0.8408	0.8219
Gear Reducer	1.0000	1.0000	0.9996	0.9985	0.9964	0.9927	0.9869	0.9780	0.9654	0.9485	0.9264
Roller Bearings	1.0000	1.0000	0.9999	0.9997	0.9993	0.9987	0.9976	0.9960	0.9937	0.9906	0.9864
Shafts	1.0000	0.9927	0.9848	0.9770	0.9690	0.9610	0.9528	0.9441	0.9352	0.9261	0.9168

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Ball Bearing	0.0000	0.0000	0.0000	0.0001	0.0002	0.0003	0.0005	0.0007	0.0009	0.0012	0.0015
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Gear Reducer	0.0000	0.0003	0.0013	0.0031	0.0057	0.0091	0.0133	0.0189	0.0256	0.0336	0.0430
Roller Bearings	0.0000	0.0001	0.0002	0.0006	0.0010	0.0016	0.0024	0.0034	0.0046	0.0060	0.0077
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9205	0.8405	0.7666	0.6960	0.6292	0.5655	0.5016	0.4402	0.3820	0.3268

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995)

Table D-7
Reliability Analysis, Dam Gate Machinery

Component/Block	Quan.	Failure Rate*	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α, Yrs	Duty Factor, d
Couplings	10	1.4054	misalignment	1.0	1.00	2	40.6131	0.007
Ball Bearing	4	1.6445	wear	1.0	1.00	2	34.7082	0.007
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798	0.007
Worm Gear Box	1	5.0000	wear	3.0	1.10	2	12.5571	0.007
Plain Bronze Bearings	16	2.8201	wear	3.0	1.10	2	22.2635	0.007
Spur Gearset	6	3.2232	wear	3.0	1.10	2	19.4792	0.007
Shafts	4	0.9298	fracture	1.0	1.00	2	61.3870	0.007
Sprocket	2	Information not Available						

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50	63
Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
Couplings	1.0000	0.9991	0.9983	0.9974	0.9966	0.9957	0.9948	0.9940	0.9931	0.9923	0.9914	0.9892
Ball Bearing	1.0000	0.9990	0.9980	0.9970	0.9960	0.9950	0.9940	0.9930	0.9920	0.9910	0.9900	0.9874
Brake	1.0000	0.9987	0.9974	0.9961	0.9949	0.9936	0.9923	0.9910	0.9898	0.9885	0.9872	0.9839
Worm Gear Reducer	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Spur Gearset	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Plain Bronze Bearings	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Shafts	1.0000	0.9994	0.9989	0.9983	0.9977	0.9972	0.9966	0.9960	0.9954	0.9949	0.9943	0.9928

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Ball Bearing	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Worm Gear Reducer	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003
Spur Gearset	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Plain Bronze Bearings	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
	1.0000	0.9839	0.9681	0.9525	0.9372	0.9221	0.9072	0.8926	0.8782	0.8641	0.8502	0.8149

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995)

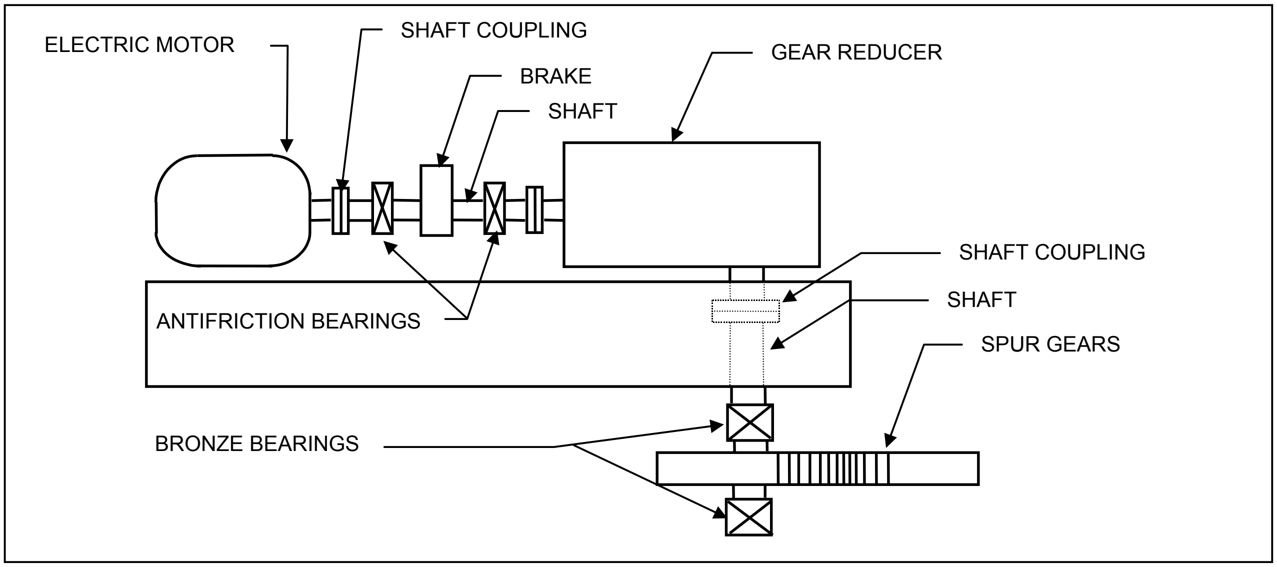


Figure D-1. Miter gate machinery

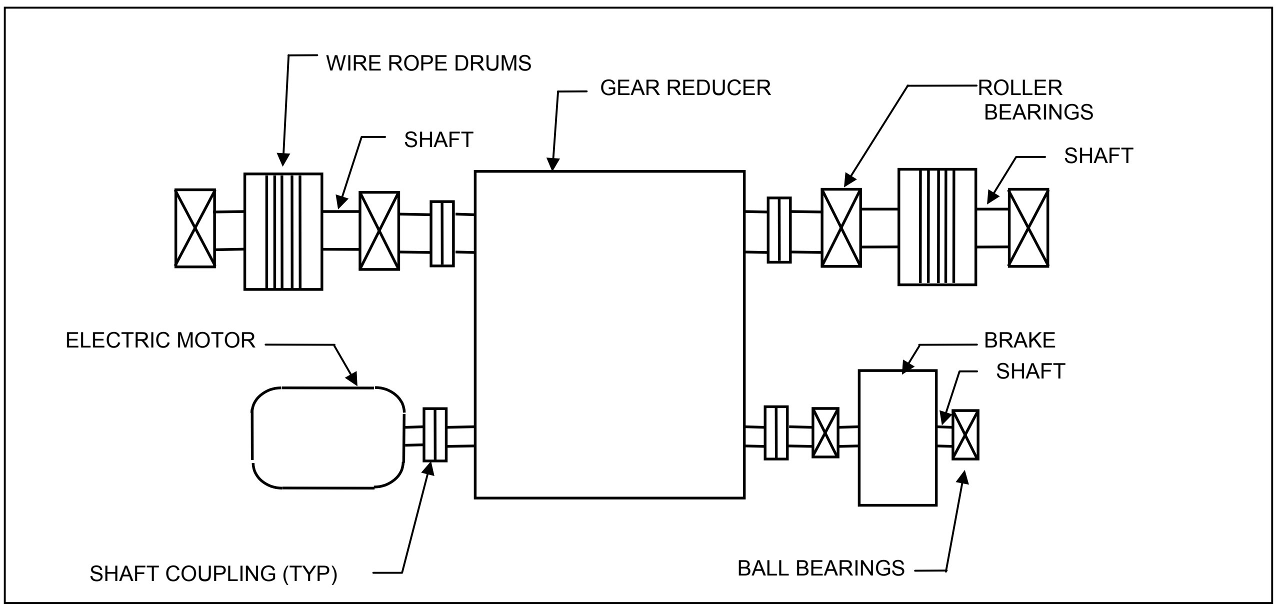


Figure D-2. Tainter valve machinery

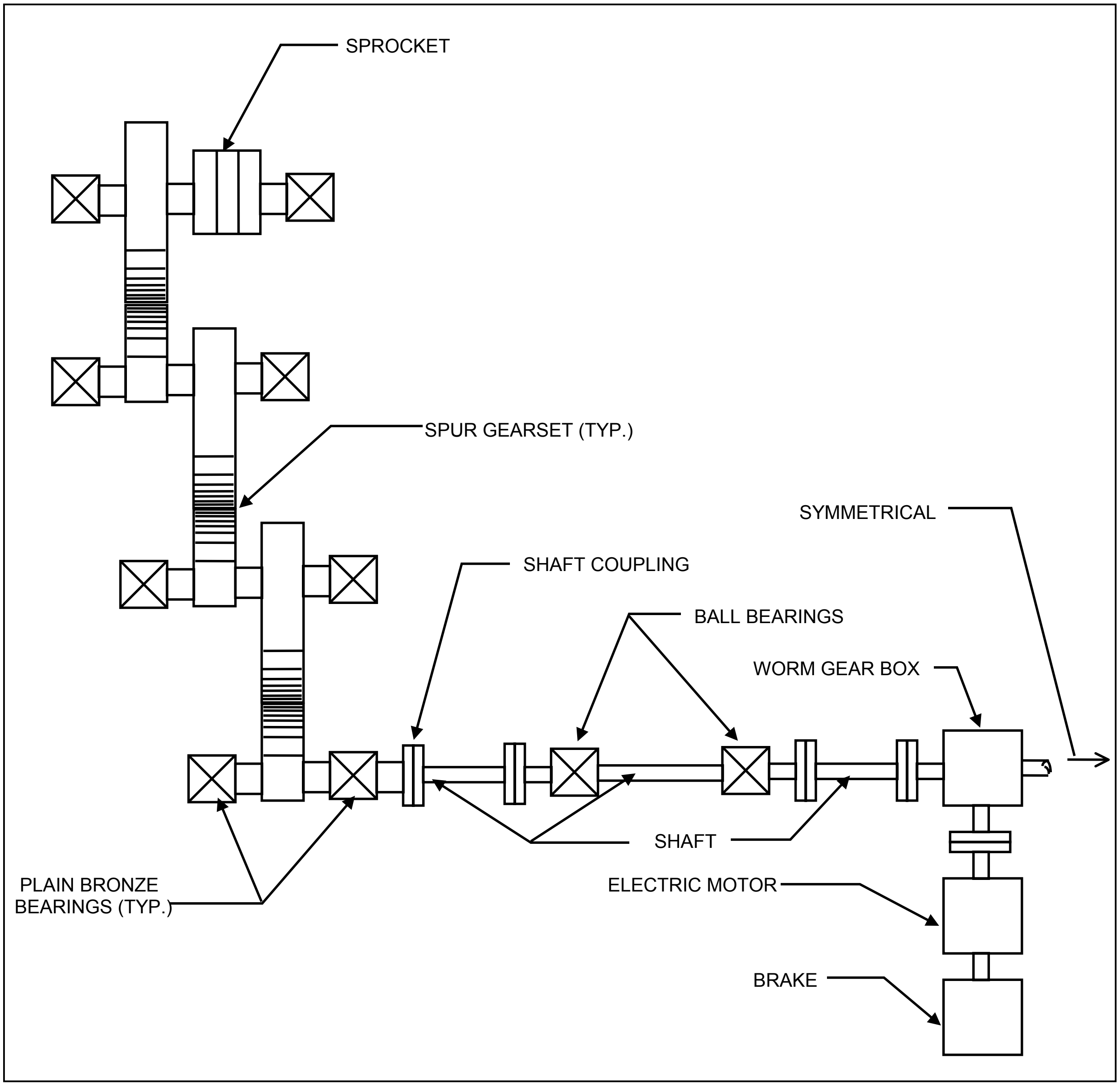
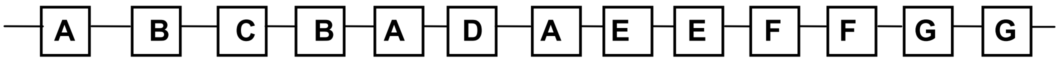


Figure D-3. Dam gate machinery



A - COUPLING
B - ANTIFRICTION BEARING
C - BRAKE
D - GEAR REDUCER
E - PLAIN BRONZE BEARING
F - SPUR GEAR
G - SHAFT

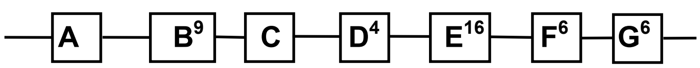
- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts.

Figure D-4. Lock machinery basic and mission reliability diagram

A - SHAFT COUPLING
B - BALL BEARING
C - BRAKE
D - GEAR REDUCER
E - ROLLER BEARING
F - SHAFT

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts, and hoist drums and wire rope.

Figure D-5. Valve machinery basic and mission reliability diagram



A - BRAKE
B - SHAFT COUPLING
C - WORM GEAR BOX
D - BALL BEARINGS
E - PLAIN BRONZE BEARINGS
F - SPUR GEAR SET
G - SHAFTS

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts, and chain sprocket.

Figure D-6. Dam machinery basic and mission reliability diagram